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5

A Producible Component

5.1 INTRODUCTION

The methodology described in Chapter 4 yields a design layout that gives geometric definition to the product and incorporates knowledge gained from testing physical prototypes. In a limited sense, the end product (the system's architecture and the components that make up the assembly) is sufficiently defined to allow copies of the product to be fabricated. This cannot, or should not, be deemed a production release since no effort has been in expended in designing tooling or gaging. Both the design of the product and the production process must be completed to bring the product development cycle to a successful conclusion.

At this stage, the design layout and prototypes contain the necessary elements to complete the product development cycle; but this knowledge is not sufficient to ensure a producible design. Also, in the event that a company either wishes to retain the proprietary knowledge gained to this point or is working on a classified project, it may not be able to share the design layout with subcontractors so that they can transform the product design into the required production capability.

The design layout contains the seeds for the design of a production process where the major design criteria include producibility. The topics of this chapter deal with a second methodology (Figure 5-1) that uses the layout to develop both the tooling and gaging designs needed to create a producible product. Embedded

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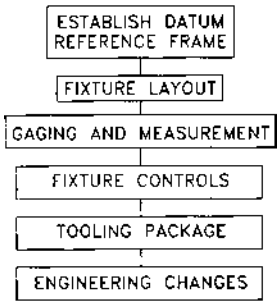

FIGURE 5-1 Six-step methodology for a producible component.

within the methodology are techniques that help resolve problems identified in developing the design layout and prototypes. The working drawings that result (e.g., product assembly, component details, gage and fixture drawings) allow production planning to specify and acquire the capabilities needed to place the product in true production.

To provide a concrete example and illustrate the various steps in the design process, the solenoid pump (see Figure 5-2), briefly described in Chapter 4, is used here. The individual elements of the assembly are discussed ahead, with numbers corresponding to the balloons in the figure. The initial version of the pump design, prior to simplification, is used to illustrate the component design process.

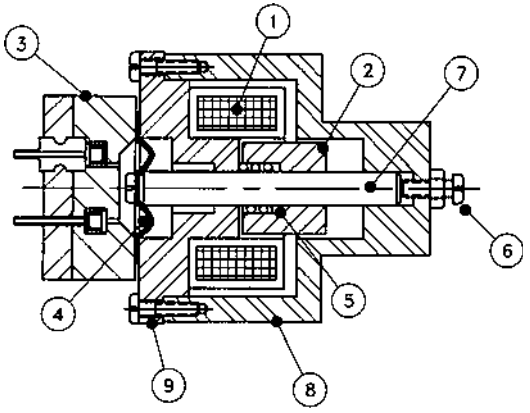

FIGURE 5-2 Pump assembly (same as Figure 4-4).

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The pump is a steel-clad assembly, consisting of an electrically energized coil (1) of insulated wire that produces a magnetic field within the coil. The coil surrounds a movable iron core (2), which is pulled to a central position with respect to the coil when the coil is energized by sending current through it. The iron core is known as the armature or plunger.

The solenoid pump consists of a hydraulic loop assembly (3), a diaphragm (4), and a spring (5) that returns the armature each time the coil is de-energized and performs the pumping action. There is a screw (6) with a lock nut to adjust the flow volume of the pump. The core is mounted on a piston-like rod (7) contained in two bores. These bores are features found in the pump body (8) and the endcap (9).

5.2 STEP ONE: THE DATUM REFERENCE FRAME

As emphasized in previous chapters, the critical element in describing a component is selection of the datum reference frame. The design layout provides the relationships among components in the assembly that, in turn, allow the DRF to be identified. Hence, the layout is the starting point necessary to detail individual components.

The concurrent engineering team must determine that singular set of part features that will orient the component in three-dimensional space in its next assembly position. This set of interrelated part features is identified as the functional datum reference frame. Several combinations of features on each component of the solenoid pump could establish a DRF. A useful technique to identify the appropriate DRF for a component is to generate a list of candidate datums by looking at the surfaces where the mating components contact each other. From this list, the various combinations of these interfaces (including precedence) are collected and provide the alternative DRFs. The team must decide which of these possible choices is most critical as it relates to function and manufacturability—which one provides the component's unique location in space.

In this example, the efforts are concentrated on the pump body and the endcap. The details of these components are shown in Figures 5-3 and 5-4. Each of these has a number of features that could be used as elements in creating a DRF. The pump body has a series of three internal coaxial bores, two external diameters, eight drilled and tapped holes, and a planar surface, all of which could become elements in constructing the functional DRF. Likewise, the endcap has four parallel, planar surfaces, three external diameters, a series of eight clearance holes, and three central coaxial bores. Any of these geometric features (either singularly or in concert) could serve as an element of a DRF.

However, from both a functional and manufacturing standpoint, only one of the combinations relates the component to the assembly in the manner the

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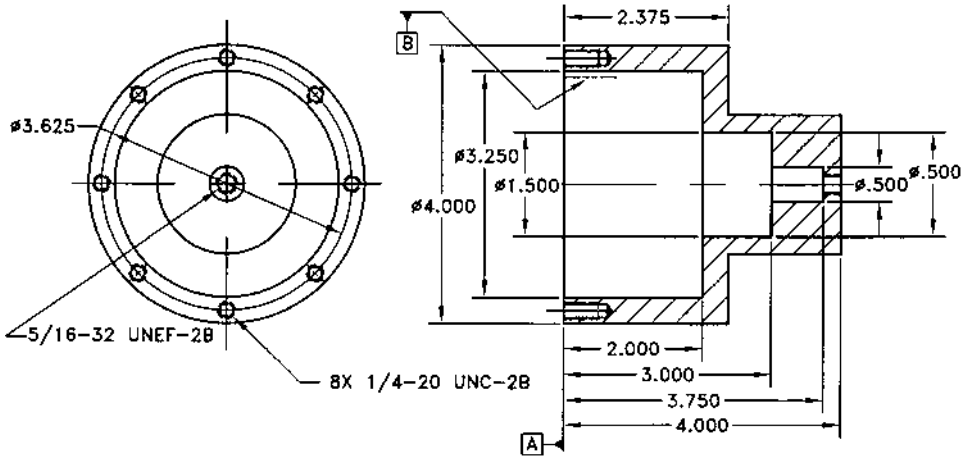

FIGURE 5-3 Preliminary detail for pump body (no geometric tolerance specified).

designer envisioned. This set of features, the functional DRF, will position each part with zero degrees of freedom when the part is nonaxial, or with 1 degree of freedom if it is a typical axial part.

After the list of DRF candidates for this example was evaluated, the following features that hold the two case sections together were identified as the most critical characteristics for assembly. The primary datum feature on the pump body is identified as the mating interface (the planar surface) and is designated as

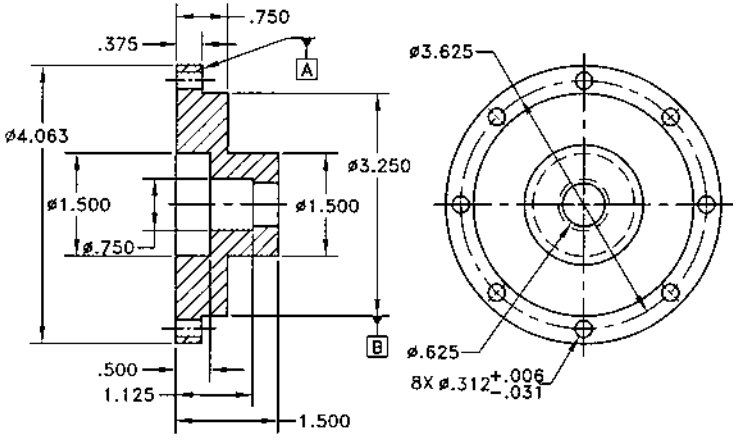

FIGURE 5-4 Preliminary detail for endcap (no geometric tolerance specified).

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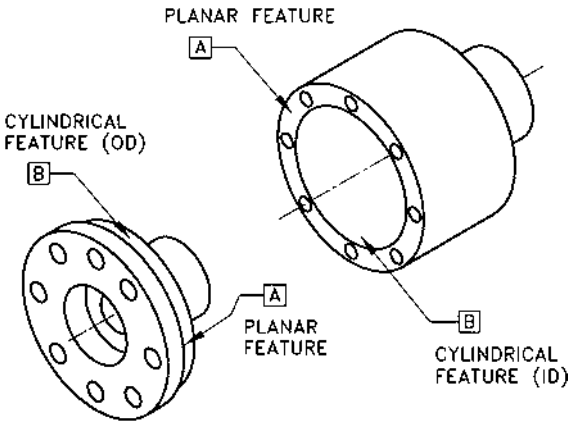

FIGURE 5-5 Pump body and endcap datums.

datum *A* (see Figure 5-5). This planar surface on the component, where it contacts a similar surface on the endcap, is the primary feature that provides kinematic orientation of the component within the assembly.

To provide satisfactory functional constraint of the part in three-dimensional space, additional datums must be identified. Based on team discussions, the secondary datum is determined to be the internal diameter on the pump body, identified as datum *B* in the figure, that locates the two case elements so that the bores in which the rod slides will be coaxial. Because of the limited penetration of the diameter of the mating cap, datum *B* is restricted to the area indicated by the chain line in Figure 5-3.

For this part, the only unconstrained motion left involves rotation about the axis established by datum feature *B*. This motion could be constrained by using the set of drilled and tapped holes that would stop rotation. However, since no asymmetrical features need to be controlled for rotational position, a tertiary datum is not specified. The hole pattern has a symmetry that eliminates the need for the part to be "clocked"; these holes could subsequently be related to the DRF by a positional tolerance.

The results of this process are documented in Figure 5-3 for the pump body. An identical procedure is applied to the endcap with similar results shown in its detail (Figure 5-4).

Once the datums are selected, they must be qualified through the use of the appropriate geometric form controls and interrelated to form the DRF. This interrelationship of the datum features through the use of controls such as orientation (e.g., perpendicularity) will avoid incomplete engineering requirements. In the example, specifications to interrelate the datums might also require locational

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information (a positional tolerance) if the eight-hole pattern were used as the tertiary datum, because the holes would have to be related to the other datum features. This could be done by providing basic dimensions and a positional control where the control's datum reference frame consists only of the primary datum.

In any event, when the component definition is used to develop prototype parts, all samples of the component should be built using the basic dimensions and associated geometric tolerances to determine target sizes and locations. The target values are not necessarily the nominal dimensions but should be developed using the appropriate boundary extremes that yield useful design-related information from the testing database.

The engineering team will find it impossible to complete the component design unless each part has been placed within the assembly and all the functional relationships have been defined. This argues for completing the design layout (Chapter 4) of the assembly before attempting to design or fabricate any constituent components. The release of component details to manufacturing prior to agreement on the design layout will inflict engineering changes on the process as the assembly definition is eventually completed, possibly after initiation of production. A more germane point is that manufacturing personnel may be allowed unwarranted, undesired, and possibly unrecognized latitude in completing the product definition if the team abdicates its responsibilities at this point in the cycle.

5.3 STEP TWO: THE FIXTURE LAYOUT

Using the DRF specified in the first step of component design, a fixture layout is developed that replicates the spatial location of the component in the next assembly position. In simple cases, this fixture layout will simulate the mating component at all assembly interfaces. In more difficult cases, datum features, such as tooling holes, bosses, or tabs, may need to be added to the component design, providing features of sufficient size and geometric form to allow proper part fixturing and complete kinematic control. The fixture layout then takes on additional geometric characteristics in order to provide the locating and holding surfaces necessary for workholding. A more complete discussion of fixture design is found in Chapter 12.

To illustrate how the fixture simulates the mating part, Figure 5-6(a) shows a simple assembly. Figure 5-6(b) describes the production fixture and shows how it mimics the mating component, simulating the next-higher level of the assembly. While there may be considerable work to be performed to complete the fixture design, the example illustrates the basic concepts around which a fixture can be built. Prominent among these concepts is the functional DRF with its ability to drive the fixture design. Further expansion of the principle is demon-

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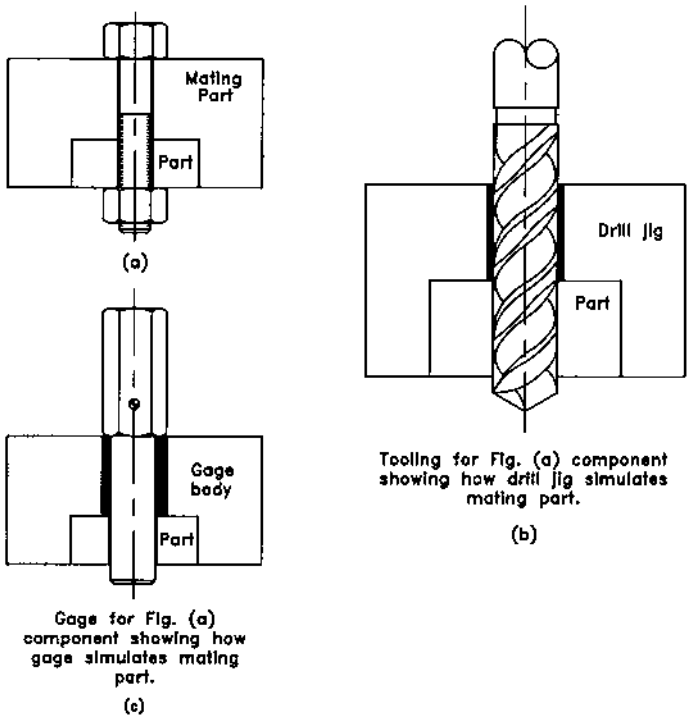

FIGURE 5-6 Example of simple design methodology.

strated in Figure 5-6(c), where the gaging fixture (functional gage) is also designed using the DRF identified in step 1.

For this pump assembly, a fixture layout is prepared for each of the components analyzed in step 1. These fixture layouts, containing both component and fixture, will replicate the next level of the assembly. As a consequence, the fixture simulates the mating part, reflecting its geometry at virtual condition, and locates each component in a singular position in three-dimensional space that replicates its actual position when assembled.

With the fixture layout in hand, the design team should add gaging elements for each of the critical and major part features that must be related to the DRF. Each of these component features is necessary to ensure part interchangeability, assembly, fit, or function. The gaging elements take their size, form, and location from corresponding features on the mating component of the part inspected by the fixture.

These fixtures are illustrated in Figures 5-7 and 5-8. In the case of the gaging fixture (Figure 5-7), the figure shows the geometric similarity between

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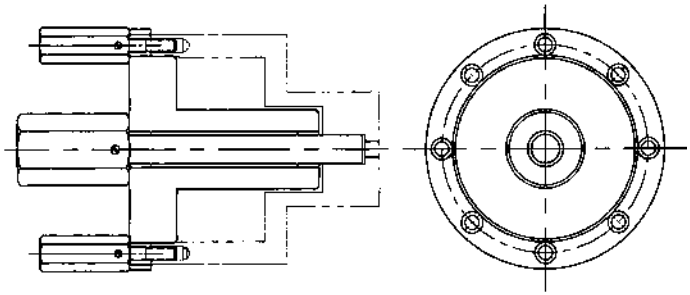

FIGURE 5-7 Functional gage for pump body.

the fixture and the mating component, particularly in the manner in which it locates the part. Using gage datums (datum feature simulators) that are identical to the locating features on the mating part, or as near to identical as manufacturing necessity allows, provides the desired location. They also become the basis for the design of the functional gages (the visible lines in Figures 5-7 and 5-8) that would be used if the economics justify the expenditure. The datum surfaces could be incorporated in a measurement fixture and used for setup purposes if CMMs or surface-plate inspection techniques are used to generate variables data.

Replacing the bushings that receive the plug gages with drill bushings alters the basic design of the gaging fixture. This creates the drill jig for the endcap illustrated in Figure 5-9. The design of the drill jig again simulates the mating component and serves to minimize possible process variation. While not a complicated example, it does show how the component design carries the seeds of the tool and gage design.

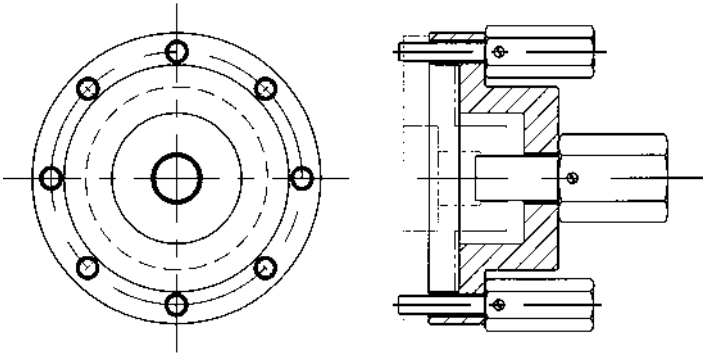

FIGURE 5-8 Functional gage for pump endcap.

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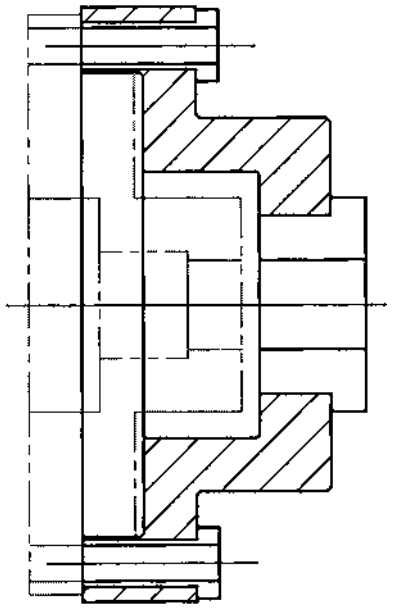

FIGURE 5-9 Drill jig for endcap derived from functional gage.

When manufacturing equipment capable of single-setup machining is available, tooling such as the drill jig may not be necessary. In this case, the exterior of the pump body could be machined using the workholding fixture shown in Figure 5-10. This would be mounted on a three-axis turning/machining center and all the critical, interrelated part features would be roughed and then finish-

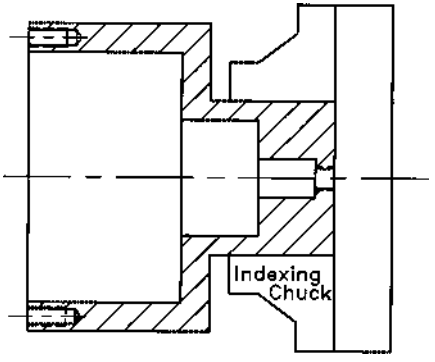

FIGURE 5-10 Workholding example for single-setup machining of pump body.

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machined in this single setup. With this processing technique, all the datum features and the remaining functional features could be generated in a single setup, eliminating, or at least reducing, process errors. Since they are all generated within the single setup (a single, process DRF), the level of variation found is dependent on the machine's capability and is not influenced by multiple DRFs being chained together. Similar comments could be made for the endcap. Figure 5-11 illustrates the corresponding workholding fixture.

These functional gaging—and processing—fixtures have unique capabilities not completely duplicated by surface-plate or CMM inspection. They not only ensure the interrelationship of the datum features forming the DRF but also provide the framework within which the part features may be gaged for interchangeability. Both capabilities are simultaneously incorporated into the gaging fixture when the functional DRF is the basis for the design of the tooling. Functional fixtures provide a functional check as distinguished from a series of independent measurements (such as performed on the CMM). The latter technique does not emulate the true relationship used for verifying product function and assembly.

Part definitions that include large tolerance values relative to the feature dimension may be inspected using CMMs and the resulting information used to assess function and assembleability. As the precision level increases (i.e., tolerance values become smaller relative to the part dimension being inspected), measurement uncertainty associated with CMM discrete-point inspection methods can begin to dominate the inspection results. With extreme precision and a stable process that produces an acceptable and functional product, the CMM still proves to be a satisfactory way to monitor production. However, a point will be reached where measurement uncertainty prevents these discrete measurements from providing the desired functional check; measurement error may become the dominant portion of the resulting measurement. The measurement planner must under-

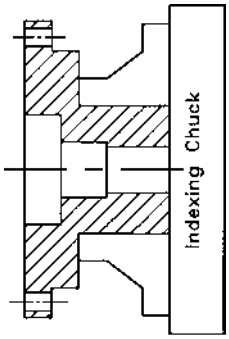

FIGURE 5-11 Workholding method for single-setup machining of endcap.

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stand the manufacturing and inspection processes and select an inspection tool appropriate to the task. The selection of inspection techniques is similar to the selection of the process operations needed to fabricate the part and deserve to have the same level of importance attached to them. In high-precision situations, the discrete-point inspection measurements are useful for monitoring the process but may not ensure complete interchangeability.

The gage shown in Figure 5-7 will also determine the virtual condition of datum *B*, which includes a perpendicularity requirement and ensures that it is within the upper size limit. It could, as shown, include an assessment of the virtual condition of the largest diameter, the virtual condition of the smaller diameter, and the diameter's height. Maximum wall thickness of the case section can also be assessed.

The fixtures illustrated in Figures 5-7 through 5-11 should be concurrently designed as a set, to ensure that all four fixtures conform to the same functional design requirements. The design of the workholding fixture must complement the design of the functional gage or gaging fixture for the same component.

5.4 STEP THREE: GAGING AND MEASUREMENT

The team's next task is to use the functional DRF and the features it controls to determine whether any of the interrelated features, both critical and major, require inspection. The set of features that together form the DRF or any features referenced to the DRF may require Go, Not Go, variables, attributes, or functional gaging.

Figure 5-6 clearly demonstrates that the inspection fixture design is dictated by the choice of the DRF, as is the design of the production fixture. Structured design techniques prevent tool and gage designers from using discretion in the creation of production and inspection tooling packages that may violate design intent. The concurrent engineering team identifies and addresses the variability of the production process before hard tooling is purchased; the decisions relating to the variability are then communicated as specific design rules to be used in generating the gaging and inspection packages.

While the example in Figure 5-6 was intentionally kept simple for discussion, it is obvious that the typical industrial part is more complex. This makes the design process much more difficult. With complex parts it becomes imperative that the functional DRF is used as the starting point leading to optimum tooling and gaging designs. This crucial design focal point is to be preferred over the arbitrary choice of locating surfaces that arise when components and tooling are designed by numerous designers making individual and isolated decisions. This is an argument for an organized and logical approach to the design rather than an unorganized but possibly rapid execution of a production design that subsequently requires change.

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The gaging fixtures shown in Figures 5-7 and 5-8 are the Go and functional gages based on the functional requirements identified by the team. The "function" gaged is component interchangeability based on the Taylor principle.

Variables data could be obtained from the virtual condition functional gage by adding dial indicators, air, electronic, or other metrological instruments. When variables data is required to assess process capability, the team will specify the inspection report to be used and the charting method to be implemented.

An illustration of the inspection database is shown in Figure 5-12. This table was generated to show the information required when the location of the hole pattern is measured to determine interchangeability.

The first two columns include a very unique set of *x*- and *y*-values (deviations) in inches. The hole size shown in column 3 is the largest-diameter cylinder perpendicular to the primary datum that will pass through the hole. The *x* and the *y* deviations from basic position (shown in columns 1 and 2) are the deviations of the axis of this cylinder from its basic or true position.

Column 4 is based on a calculation where the virtual condition (VC) of the hole is subtracted from the hole size in column 3. This value is the positional

Inspection Report
Product Specification: 8 x Ø .312
(Solenoid Pump Clearance Holes)
Virtual Condition: Ø.312 - Ø.031=Ø.281(VC)

Characteristic Sample Number	Column 1 X Deviation	Column 2 Y Deviation	Column 3 Size	Column 4 Size - VC	Column 5 $2\sqrt{x^2+y^2}$	Column 6 (Column 4 minus Column 5)
1	+.007	-.006	.315	.034	.018	.016
2	+009	+.008	.319	.038	.024	.014
3	-.006	+.008	.314	.033	.020	.013
4	-.006	-.007	.318	.037	.018	.019
5	-.009	+.008	.317	.036	.024	.012
6	+.008	-.006	.315	.034	.020	.014
7	+.007	+.006	.315	.034	.018	.016
8	-.004	-.006	.314	.033	.014	.019

Mean of Column 6 = .01538
Range of Column 6 = .007

FIGURE 5-12 Inspection database.

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tolerance available when the hole is at its basic location in x and y. Note that the value is a function of the hole size in column 3; as the hole size increases, there is potentially more tolerance available; the opposite is true as the hole decreases in size.

Column 5 is a calculation based on the deviation in x and y for each hole. The formula, two times the square root of the sum of the squares of x and y, converts the data in columns 1 and 2 into positional tolerance diameters for each of the holes based on its deviation in x and y.

Column 6 is the difference between columns 4 and 5. The larger this value becomes, the further one is from the "edge of the cliff" of not achieving interchangeability and, therefore, assembleability.

There may be a temptation to utilize the information from the inspection report to chart positional tolerances. It must be understood that any attempt to chart geometric characteristics involves significant preliminary work to understand the underlying statistical distributions. The typical GD&T characteristic does not follow a univariate Guassian distribution, which makes investigation into the type of distribution both difficult and imperative.

5.5 STEP FOUR: FIXTURE CONTROLS

Once the inspection and measurement requirements have been determined, these relationships are embodied in geometric controls and used to complete the preliminary design layout and the working drawings. The separate fixture designs, containing functional acceptance criteria embedded in them, are used to guide the team in completing the layout. Both the layout and the fixture designs are not complete until geometric controls have been added.

Returning to the pump example, the functional features—the critical and major characteristics still contained in the design—must be incorporated into the fixture, related to the fixture DRF, and given geometric tolerances. These requirements, including any appropriate size tolerances, are the gage tolerances. Figures 5-13 and 5-14 show the results for the component details, with Figures 5-15 and 5-16 illustrating the resulting gages.

The completed design layout and the fixture drawings will be the basis for preparing the component detail drawings. At this level, the tooling package, to be discussed ahead, provides complete product definition for each component, ensuring that design intent is maintained. Additionally, the detail definition contains all the necessary information to ensure integrity of the assembly as the components are produced.

In the event that the component will be measured using surface-plate techniques, the part would be set up in a rotary table and the measurement process sheet would describe each step required to generate the database. Inspection process sheets would also describe all the necessary inspection hardware to simulate

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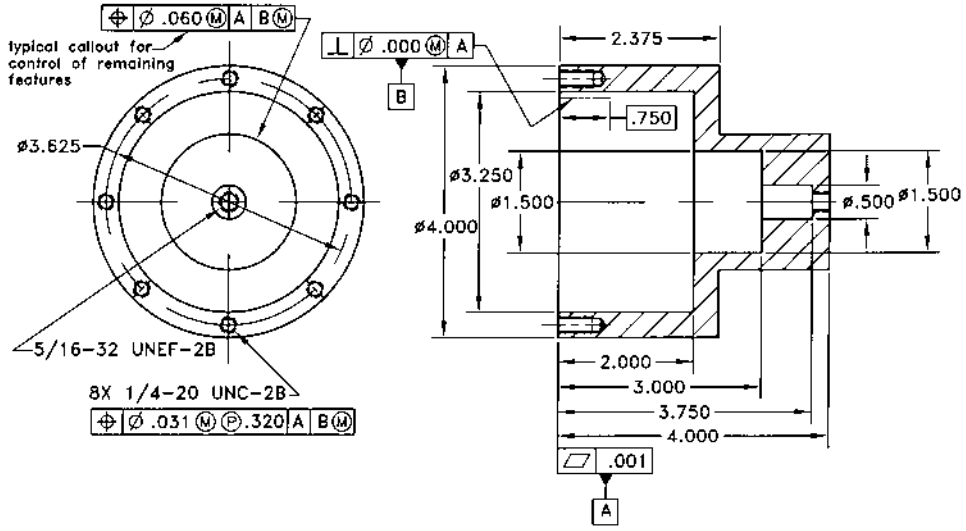

FIGURE 5-13 Detail for pump body with GD&T added.

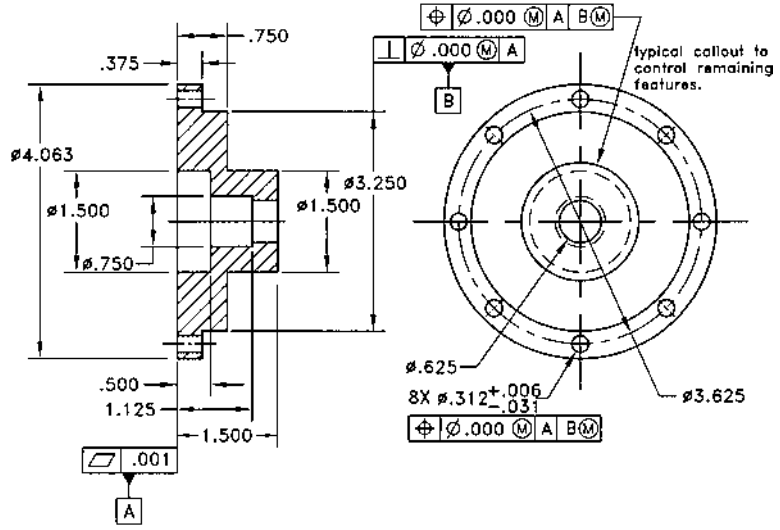

FIGURE 5-14 Detail for endcap with GD&T added.

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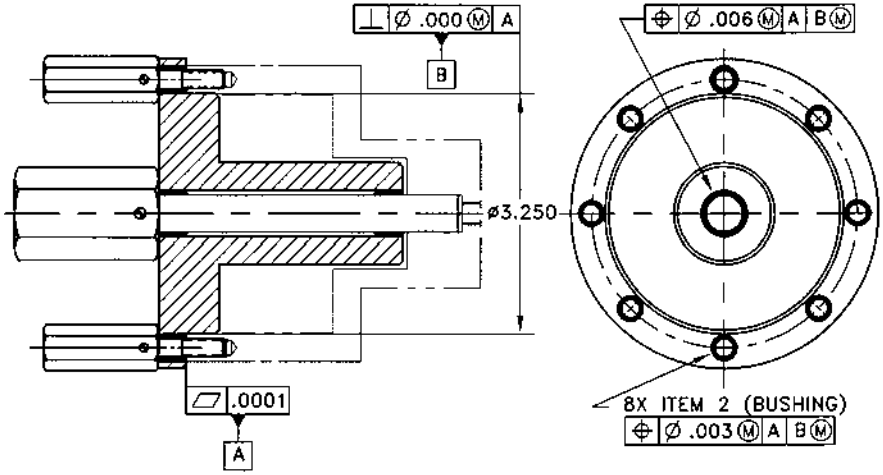

FIGURE 5-15 Pump body functional gage with selected GD&T specifications added.

the effects of the fixture. The inspection process is planned and documented to the same degree as the manufacturing process.

If measured on a CMM, the setup and sequence of operations would again be covered on a process operation sheet to ensure that the same database verifying the intended characteristics is generated. The part could be set up using standard

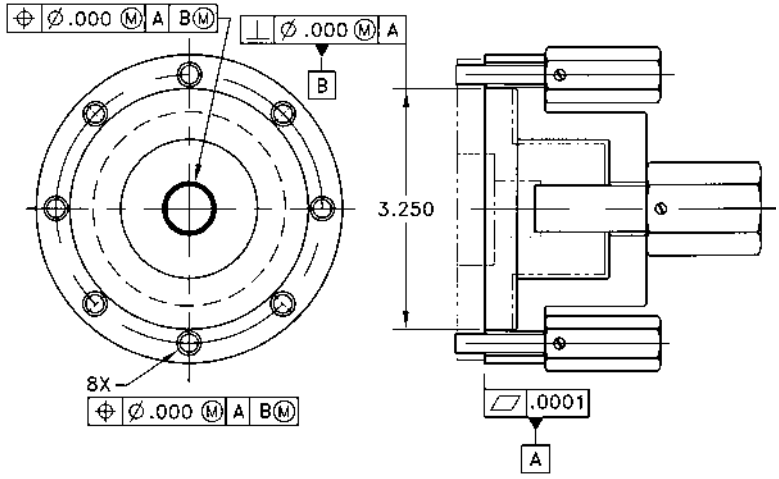

FIGURE 5-16 Endcap functional gage with selected GD&T controls added.

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inspection components that can simulate the fixture from step 2 or with a fixture specifically designed—step 2 again—for measurement purposes.

Where fixture gages similar to the functional gages shown in Figures 5-15 and 5-16 are used to generate the variables database, the fixture layout includes optional sweep gages to contact those part characteristics used in determining process capability.

It should be emphasized again that checking process capability is not necessarily the same as checking for component function. The design team should engage in appropriate discussions related to the differences between these checks. In many instances, an inspection process that samples a surface by generating a point data set (e.g., a CMM) does not converge to a functional check until a large number of points are taken. With industrial emphasis on cycle-time reduction—sampling based on the minimum number of points required by the software and high sampling velocities—this divergence of inspection methods sometimes gets lost in the rush to move the part into production. Low cycle times may be obtained by increasing measurement uncertainty. This tradeoff must be consciously evaluated.

5.6 STEP FIVE: TOOLING PACKAGE

After the controls have been added to the fixture, both the component detail drawing and the fixture layout should be bundled together for manufacturing planning or requests for quotation. The team must make certain policy decisions at this point. Two explicit areas involve the scope of information to be released to suppliers and the tolerancing policy that will be applied to the inspection methods.

The first of the decisions involves how the necessary endproduct definition is provided to the supplier. If the work is to be retained by the firm and members of the appropriate departments were involved with the simultaneous engineering of the product, the design layout is available to all concerned parties. The part detail and the fixture layout of each fixture/gage (or equivalent inspection process plans for use of equipment such as a CMM), including DRFs, geometric controls, and tolerances, are sufficient to provide complete product and process definition.

Other options occur if the part is to be subcontracted. If the supplier is a member of the concurrent engineering team, possibly the result of a long-term relationship, then the package provided would be the same as mentioned above. If not part of the product development team, the contractor may not be given the design layout and he or she would not receive any of the fixture/gage layouts since these would be considered proprietary information. To ensure conformance to the product definition in such a case, the contractor would be provided with hard gages and/or appropriate inspection process plans. These gages and process plans would prevent proprietary or classified information from being re-

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leased to the contractor while still providing complete definition of the product requirements.

The other decision to be made concerns the gaging or inspection policy to be employed when the gages are toleranced. The issues that must be considered in choosing a policy operate at both the economic and technical levels. At the economic level, the issue becomes the question of who accepts the risk associated with nonfunctional parts. Essentially, three policies (Galdman, 1971) may be followed:

1. The *optimistic policy*, where the buyer assumes the risk of nonfunctional components
2. The *pessimistic policy*, where the manufacturer assumes the risk of nonfunctional components
3. The *tolerant policy*, where the risk of nonconformance is shared by the buyer and the manufacturer

The technical issues (using gage design as the example) revolve around the choice of gage limits with respect to drawing limits. The technical concern is the relationship of the physical measurements embedded in the gage design with respect to the limits established by the engineering drawing. The problem requires assessing measurement uncertainty and then choosing gage dimensions that place gage limits and corresponding uncertainty zones within the range of drawing dimensions in a manner acceptable to both producer and customer—a contractual arrangement. This is illustrated graphically in Figure 5-17.

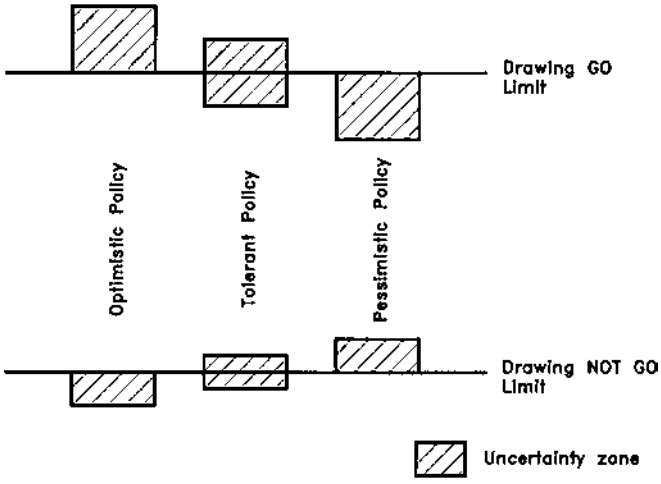

FIGURE 5-17 Relationships drawing limits, Go/Not Go gages, and uncertainty.

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Just how these policy decisions could affect the development of the tooling package is seen in the situation where the components are made externally and the supplier did not participate in the simultaneous engineering activities. Hard tooling and gaging should be fabricated—again recognizing that process plans for CMM inspection may be substituted—and provided to the supplier in lieu of the tooling and gaging layouts. This ensures communicating the team's explicit definition of product conformance beyond what may be contained in the detail drawings provided for fabrication and allows no discretion in the interpretation of the controls contained in the product definition. Actual fixtures and hard gaging will ensure that the supplier understands the design requirements when bidding on the work. However, in manufacturing the tooling or gaging, gage tolerances must be established that require choosing one of the policy options. The specific gaging policy used in creating the tooling and gaging layouts must be communicated explicitly. As should be obvious, this choice has a great effect on project economics because it directly affects the choice of process and yield.

All the fixtures described or outlined above are expected, as the result of the simultaneous engineering effort, to provide the basis for production line design and quality assurance activities that ensure conformance to specification.

5.7 STEP SIX: ENGINEERING CHANGES

While one of the team's goals is to achieve production with zero engineering changes, this level of perfection is not likely to be obtained. Thus, any tentative changes should be analyzed guided by the product design (both assembly and detail level) and the fixture layouts. It is also obvious that these changes should be approved and put into effect only after the members of the original concurrent engineering team reach consensus. Any design changes will be tentatively added to these layouts and an analysis done to confirm the effects on the product design. This is done before the detail drawings are changed.

A specific example where this situation might occur is when another supplier, not part of the original process, cannot utilize the fixtures or workholding devices established by the concurrent engineering team. Under these conditions engineering changes would be required. These changes should not be approved until analyzed using the design and fixture layouts. The changes should be incorporated into these layouts to determine if the design intent, assembleability, or the producibility has been compromised. In the event that change appears necessary, the team members affected by the change must be assembled to work on the solution to the problem; the new supplier would also participate in this analysis.

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5.8 SUMMARY

A critical step the concurrent engineering team must take involves refining the information contained in the design layout to give definition to the assembly's components. This definition takes the product from "functional and feasible" to producible.

The work at this stage is accomplished by a second six-step methodology. The starting point is the design layout and the working prototypes discussed in the preceding chapter. Along with these two tangible manifestations of the product, the team also identifies possible problems in the product that need to be addressed. These suspect areas are also part of the information that guides design of a producible product.

The chapter's techniques address these concerns while completing the product definition, describing in detail the components, gaging, and tooling needed to foster economical production. The result of this endeavor is the complete design layout, individual details of the product components, and appropriate designs for fixtures and gages.

The underlying idea that drives all this work is the ever-present datum reference frame. The identification of the functional frame is the starting point for team design of the fixtures and gages. Development of these designs provides the final pieces of information necessary to finish the design layout. Once this is complete, the baseline design contained in the design package—encompassing product, tools, and gages—is the benchmark from which subsequent product decisions are made.

If this process has been carried out carefully, then the inevitable engineering changes that occur will be held to a minimum. Those that must be enacted can be evaluated in a logical and controlled fashion, reducing disruption to the manufacturing operations. The use of geometric controls to define the component, the fixtures, the gages, and the production and inspection setups is an absolute necessity to achieve these goals.

REFERENCE

Gladman, C. A., Gauging principles, CIRP Annals, **XVIV**, pp. 377–384, 1971.

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